# VIP

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## 1 The VIP scientific case and the experimental method

Within VIP an experimental test on the Pauli Exclusion Principle is being performed, together with other tests on fundamental physics principles.

The Pauli Exclusion Principle (PEP), a consequence of the spin-statistics connection, plays a fundamental role in our understanding of many physical and chemical phenomena, from the periodic table of elements, to the electric conductivity in metals and to the degeneracy pressure which makes white dwarfs and neutron stars stable. Although the principle has been spectacularly confirmed by the huge number and accuracy of its predictions, its foundation lies deep in the structure of quantum field theory and has defied all attempts to produce a simple proof. Given its basic standing in quantum theory, it is appropriate to carry out high precision tests of the PEP validity and, indeed, mainly in the last 20 years, several experiments have been performed to search for possible small violations. Many of these experiments are using methods which are not obeying the so-called Messiah-Greenberg superselection rule. Moreover, the indistinguishability and the symmetrization (or antisymmetrization) of the wave-function should be checked independently for each type of particles, and accurate tests were and are being done.

The VIP (VIolation of the Pauli Exclusion Principle) experiment, an international Collaboration among 10 Institutions of 6 countries, has the goal to either dramatically improve the previous limit on the probability of the violation of the PEP for electrons, (P < 1.7 x $10^{-26}$ established by Ramberg and Snow: *Experimental limit on a small violation of the Pauli principle*, Phys. Lett. **B 238** (1990) 438) or to find signals from PEP violation.

The experimental method consists in the introduction of electrons into a copper strip, by circulating a current, and in the search for X-rays resulting from the forbidden radiative transition that occurs if some of the new electrons are captured by copper atoms and cascade down to the 1s state already filled by two electrons with opposite spins (Fig. 1.)

The energy of $2p \rightarrow 1s$ transition would differ from the normal $K_\alpha$ transition by about 300 eV (7.729 keV instead of 8.040 keV) providing an unambiguous signal of the PEP violation. The measurement alternates periods without current in the copper strip, in order to evaluate the X-ray background in conditions where no PEP violating transitions are expected to occur, with periods in which current flows in the conductor, thus providing "new" electrons, which might violate PEP. The rather straightforward analysis consists in the evaluation of the statistical significance of the normalized subtraction of the two spectra in the region of interest (if no signal is seen). A more complex statistical analysis (such as Bayesian) is also being implemented.

The experiment is being performed at the LNGS underground Laboratories, where the X-ray background, generated by cosmic rays, is reduced.

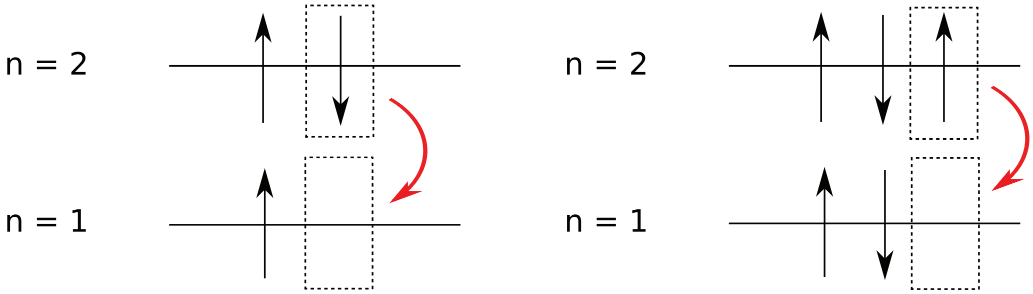


Figure 1: *Normal 2p to 1s transition with an energy around 8 keV for Copper (left) and Pauli-violating 2p to 1s transition with a transition energy around 7,7 keV in Copper (right).*

The VIP group is extending its scientific program to the study of other items of the fundamental physics, such as discrete symmetries and collpase models. Encouraging preliminary results were already obtained.

## 2 The VIP and VIP2 setups

The VIP setup was realized in 2005, starting from the DEAR setup, reutilizing the CCD (Charge Coupled Devices) as X-ray detectors, and consisted of a copper cylinder, were current was circulated, 4.5 cm in radius, 50 $\mu$m thick, 8.8 cm high, surrounded by 16 equally spaced CCDs of type 55.

The CCDs were placed at a distance of 2.3 cm from the copper cylinder, grouped in units of two chips vertically positioned. The setup was enclosed in a vacuum chamber, and the CCDs cooled to 165 K by the use of a cryogenic system. The VIP setup was surrounded by layers of copper and lead to shield it against the residual background present inside the LNGS laboratory, see Fig. 2.

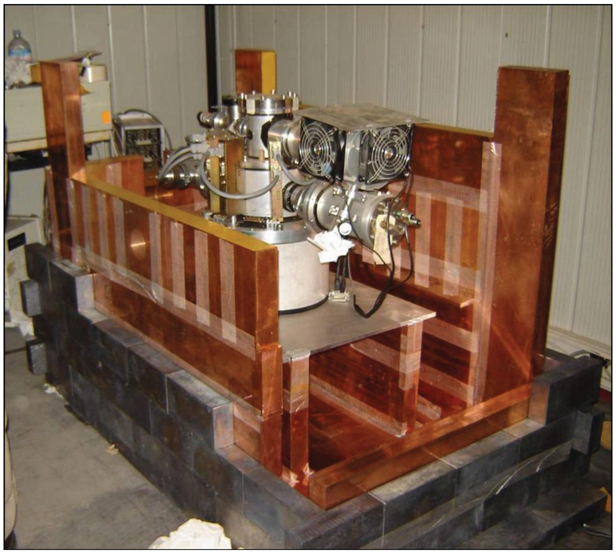


Figure 2: The VIP setup at the LNGS laboratory during installation.

Table 1: List of expected gain factors of VIP2 in comparison to VIP (given in brackets).

| Changes in VIP2 | value VIP2(VIP) | expected gain |
|---|---|---|
| acceptance | 12% (1%) | 12 |
| increase current | 100A (50A) | 2 |
| reduced length | 3 cm (8.8 cm) | 1/3 |
| total linear factor | | 8 |
| energy resolution | 170 eV(340 eV) | 4 |
| reduced active area | 6 $\text{cm}^2$(114 $\text{cm}^2$) | - |
| better shielding and veto | | 5-10 |
| higher SDD efficiency | | 1/2 |
| background reduction | | 200-400 |
| **overall gain** | | **∼120** |

The DAQ alternated periods in which a 40 A current was circulated inside the copper target with periods without current, representing the background.

VIP was installed at the LNGS Laboratory in Spring 2006 and was taking data until Summer 2010. The probability for PEP Violation was found to be: $\beta^2/2 < 4.6 \times 10^{-29}$.

In 2011 we started to prepare a new version of the setup, VIP2, for which a first version was finalized and installed at the LNGS-INFN in November 2015, and with which we will gain a factor about 100 in the probability of PEP violation in the coming years (see Table 1).

In 2018 the VIP2 setup was upgraded with new SDDs and shielding and is presently in data taking.

## 3 Activities in 2018

### 3.1 VIP2 - a new high sensitivity experiment

In order to achieve a signal/background increase which will allow a gain of two orders of magnitude for the probability of PEP violation for electrons, we built a new setup with a new target, a new cryogenic system and we use new detectors with timing capability and an active veto system. As X-ray detectors we use spectroscopic Silicon Drift Detectors (SDDs) which have an even better energy resolution than CCDs and provide timing capability which allow to use anti-coincidence provided by an active shielding.
The VIP2 system is providing:

1. signal increase with a more compact system with higher acceptance and higher current flow in the new copper strip target;
2. background reduction by decreasing the X-ray detector surface, more compact shielding (active veto system and passive), nitrogen filled box for radon radiation reduction.

In the Table 1 the numerical values for the improvements in VIP2 are given which will lead to an expected overall improvement of a factor about 100.

### 3.2 Status of VIP2 in 2018

In the VIP2 apparatus, in Spring 2018, 4 new SDD arrays with 2 × 4 SDDs detectors each (with 8 × 8 $\mathrm{cm}^2$), with a total active area of 20 $\mathrm{cm}^2$ each, were mounted close to the Cu target (see Figure 3). Moreover, an active shielding system (veto) is being implemented, to reduce the background in the energy region of the forbidden transition. This system will play an important role to improve the limit for the violation of the PEP by two orders of magnitude with the new data which are presently coming by running the VIP2 experiment at LNGS.

In November 2018 part of the lead and cooper shielding were also installed. The data taking, together with data analysis, are undergoing.

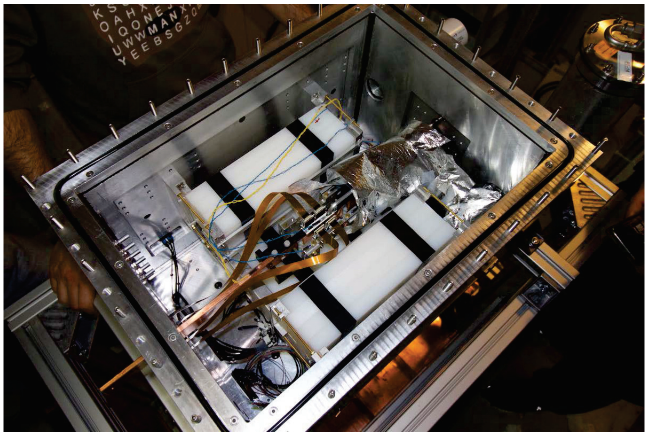


Figure 3: *A picture of the inner part of the VIP-2 setup with the new SDDs installed at LNGS .*

Data with 100 Ampere DC current applied to the copper strip was collected together with the data collected without current, representing the background.

### 3.3 Preliminary data analyses

A first set of VIP2 data was analysed by using a simultaneous fit of the "signal" and background spectra, in order to use all the information available for the background shape from the data. The obtained spectra are shown in Fig 4, together with the simultaneous fitting functions, from where a limit of the probability of PEP violation was extracted to be:

$$\frac{\beta^2}{2} \leq \frac{3 \times 67}{8.1 \times 10^{30}} = 3.2 \times 10^{-29}. \tag{1}$$

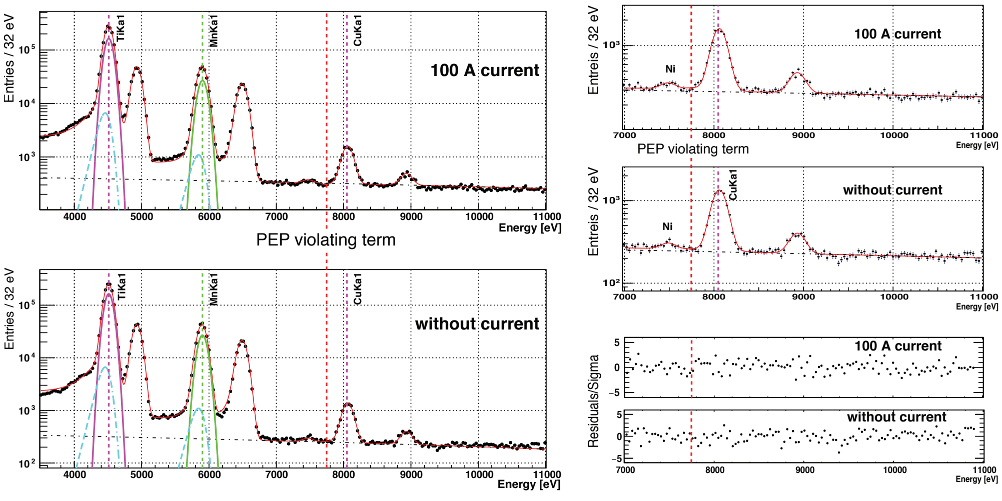
A paper is in preparation describing the new analysis and the obtained results.

### 3.4 A new data analysis

A new data analysis, considering the electron diffusion in bulk-matter process, was proposed and realised. The result:

$$\frac{\beta^2}{2} \leq 2.6 \times 10^{-40}. \tag{2}$$

was published in Entropy (2018) 20 (7), 515.



(a)

(b)

Figure 4: *A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper $K_{\alpha 1}$ transition. The Gaussian function and the tail part of the $K_{\alpha 1}$ components and the continuous background from the fit result are also plotted. (a) : the fit to the wide energy range from 3:5 keV to 11 keV; (b) : the fit and its residual for the 7 keV to 11 keV range where there is no background coming from the calibration source. See the main text for detail*

Discussions with theoreticians about the interpretation of results are ongoing.

## 4 X-ray measurements for testing the dynamical reduction models

The aim of the Dynamical Reduction Models (DRM) is to solve the so-called "measurement problem" in Quantum Mechanics (QM). The linear and unitary nature of the Shrödinger equation allows, in principle, the superposition of macroscopic states, but such superpositions are not observed in the measurement process, which is intrinsically non-linear and stochastic 1, 2). The measurement problem led to the introduction of the wave packet reduction principle which, nevertheless, does not predict the scale at which the quantum-to-classical transition occurs, nor explains the collapse mechanism.

The work of Ghirardi, Rimini and Weber 3) lead to the development of a consistent DRM known as Quantum Mechanics with Spontaneous Localization (QMSL). According to the QMSL model each particle of a macroscopic system of $n$ distinguishable particles experiences sudden spontaneous localizations, on the position basis, with a mean rate $\lambda = 10^{-16}$ s$^{-1}$, and a correlation length $a = 10^{-7}$ m. Between two localizations particles evolve according to the Shrödinger dynamics. The model ensures, for the macroscopic object, the decoupling of the interanl and Center of Mass (CM) motions. The interanl motion is not affected by the localization, whereas the CM motion is localized with a rate $\lambda_{macro} = n\,\lambda$.

Subsequently, the theory was developed in the language of the non-linear and stochastic Shrödinger equation 4, 5), where besides the standard quantum Hamiltonian, two other terms induce a diffusion process for the state vector, which causes the collapse of the wave function in space. In its final version 6) the model is known as the mass proportional Continuous Spontaneous

Localization (CSL).

The value of the mean collapse rate is presently argument of debate. According to CSL $\lambda$ should be of the order of $10^{-17}$ s$^{-1}$, whereas a much stronger value $10^{-8\pm2}$ s$^{-1}$ was proposed by S. L. Adler [8] based on arguments related to the latent image formation and the perception of the eye.

DRM posses the unique characteristic to be experimentally testable, by measuring the (small) predicted deviations with respect to the standard quantum mechanics. The conventional approach is to generate spatial superpositions of mesoscopic systems and examine the loss of interference, while environmental noises are, as much as possible, under control. The present day technology, however, does not allow to set stringent limits on $\lambda$ by applying this method. The most promising testing ground, instead, is represented by the search for the spontaneous radiation emitted by charged particles when interacting with the collapsing stochastic field [7]. A measurement of the emitted radiation rate thus enables to set a limit on the $\lambda$ parameter of the models.

The radiation spectrum spontaneously emitted by a free electron, as a consequence of the interaction with the stochastic field, was calculated by Q. Fu [7] in the framework of the non-relativistic CSL model, and it is given by:

$$\frac{d\Gamma(E)}{dE} = \frac{e^2\lambda}{4\pi^2 a^2 m^2 E} \tag{3}$$

in eq. (3) $m$ represents the electron mass and $E$ is the energy of the emitted photon. In the mass proportional CSL model the stochastic field is assumed to be coupled to the particle mass density, then the rate is to be multiplied by the factor $(m/m_N)^2$, with $m_N$ the nucleon mass. Using the measured radiation appearing in an isolated slab of Germanium [9] corresponding to an energy of 11 KeV, and employing the predicted rate eqn. (3), Fu obtained the following upper limit for $\lambda$ (non-mass poportional model):

$$\lambda < 0.55 \cdot 10^{-16} s^{-1}. \tag{4}$$

In eq. (4) the QMSL value for $a$ ($a = 10^{-7}$ m) is assumed and the four valence electrons were considered to contribute to the measured X-ray emission, since the binding energy is $\sim$ 10 eV in this case, and they can be considered as *quasi-free*. Recent re-analyses of Fu's work [8, 10] corrected the limit to $\lambda < 2 \cdot 10^{-16} s^{-1}$.

We improved the limit on the collapse rate [11] by analysing a set of data collected at LNGS with Ge detectors and an ultra-pure lead target.

A Bayesian model was adopted to calculate the $\chi^2$ variable minimized to fit the X ray spectrum, assuming the predicted (Eq. (3)) energy dependence:

$$\frac{d\Gamma(E)}{dE} = \frac{\alpha(\lambda)}{E}. \tag{5}$$

The preliminary obtained value for $\lambda$ is:

$$\lambda \leq 5.2 \times 10^{-13} s^{-1}, \tag{6}$$

in the mass proportional CSL assumption. The results was submitted for publication.

By using a similar method, we are considering the idea to perform other dedicated experiments at LNGS which will allow for 1 - 2 orders of magnitude further improvement on the collapse rate parameter $\lambda$.

### 4.1 Workshops organization

In 2018 the following events related to the physics of VIP, and, more generally, to quantum mechanics, were organized:

1. Workshop Quantum Foundation, “The physics of “what happens” and the measurement problem”, 24-26 May, 2017, Frascati, Italy.
2. Workshop Quantum Foundation, “New frontiers in testing quantum mechanics from underground to the space”, 29 November-1 December, 2017, Frascati, Italy.

## 5 Activities in 2019

In 2019 we will be in data taking with VIP2 at LNGS-INFN. The 2016, 2017 and 2018 data analysis will be finalized and published. We are, as well, going to continue the studies on fundamental physics, in particular on the collapse model by measurements of X rays spontaneously emitted in the continuous spontaneous localization (CSL) model.

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## 6 Publications in 2017

1. H. Shi *et al*, Search for the violation of Pauli Exclusion Principle at LNGS, EPJ Web Conf. **182** (2018) 02118.
2. P. Moskal *et al*, Feasibility studies of the polarization of photons beyond the optical wavelength regime with the J-PET detector, Eur.Phys.J. C **78** (2018) no.11, 970.
3. K. Dulski *et al*, Commissioning of the J-PET detector in view of the positron annihilation lifetime spectroscopy, Hyperfine Interact. **239** (2018) no.1, 40.
4. J. Raj *et al*, A feasibility study of the time reversal violation test based on polarization of annihilation photons from the decay of ortho-Positronium with the J-PET detector, Hyperfine Interact. **239** (2018) no.1, 56.
5. P. Kowalski *et al*, Estimating the NEMA characteristics of the J-PET tomograph using the GATE package, Phys.Med.Biol. 63 (2018) 165008.
6. G. Korcyl *et al*, Evaluation of Single-Chip, Real-Time Tomographic Data Processing on FPGA - SoC Devices, DOI: 10.1109/TMI.2018.2837741, e-Print: arXiv:1807.10754 [physics.ins-det].
7. E. Milotti *et al*, On the Importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle, Entropy **20** (2018) no.7, 515.

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10. P. Moskal *et al*, Feasibility study of the positronium imaging with the J-PET tomograph, e-Print: arXiv:1805.11696 [physics.ins-det].
11. K. Piscicchia *et al*, Experimental constrains on the Continuous Spontaneous Localization model from spontaneous radiation emission, PoS CORFU2017 (2018) 201, DOI: 10.22323/1.318.0201.
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13. H. Shi *et al*, Experimental search for the violation of Pauli Exclusion Principle, Eur.Phys.J. C **78** (2018) no.4, 319.

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